# Investigations on Three-Body Abrasive Wear Behaviour of Composite Brake Pad Material

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***Abstract***

Enhancement of abrasion resistance of phenol formaldehyde based composite brake pad material with various constituents viz. abrasive, filler and binder have been synergistically investigated in the present study. The influence of applied load and abrading distance on three-body abrasive wear behaviour of composite brake pad material has been studied using quartz as abrasives. Wear tests were carried out on a dry sand/rubber wheel abrasion tester. The results indicate that the wear volume loss increases with increasing abrading distance/load. However, the specific wear rate decreased with increasing abrading distance and increases with applied load. The reinforced phases such as glass fibers, silicon carbide (SiC), antimony and ferrosilicon strengthens the composite and molykote acts as lubricant which is effective barrier in preventing large scale fragmentation of phenol formaldehyde. This wear resistance is attributed to the lack of particle pull-out and the ability of the hard particles to protect the softer principal matrix from abrasion. Further, the worn surfaces were examined by scanning electron microscopy (SEM). At lower load, the presence of resin rich layer improves the bonding and surface integrity with good fiber-matrix adhesion. When the load is increased micro-cracks are formed followed by fragmentation of the constituents in composite brake pad material. The work showed that higher load brings about changes in worn surface features such as interface separation and loss of matrix as well as fiber.

***Keywords***

*Composite Brake Pad Material; Three-Body Abrasive Wear; Dispersoid Phases; Morphology of Worn Surfaces*

## Introduction

Fiber and particulate reinforced thermoset polymer composites have occupied a key role in structural and automobile applications owing to their exceptional properties of high specific strength, excellent fracture toughness and thermal, electrical, corrosive resistance. These beneficial parameters lead to the employment of polymeric composites in tribological purposes such as gears, brakes, clutches, bearings and transmission belts. Most of the brake pad materials are made up of non-asbestos organic (NAO) based friction materials which is a multi ingredient systems containing more than 10 ingredients in order to achieve the desired amalgam of performance properties. The ingredients are classified into four major functional groups such as binder, reinforcements, frictional modifiers (abrasives and lubricants) and fillers which perform synergistically in controlling the friction and wear of brake pad. The binder is the heart of the composite which holds the ingredients together and maintains the structural integrity. The reinforcement fibers strengthen the matrix, while the friction modifiers stabilize the friction coefficient and the wear rate. Fillers are of two types namely, the functional fillers and space fillers. Thermoset phenol formaldehydes are mainly used as binder due to its better mechanical properties, moderate thermal stability and wetting ability with the various ingredients. Adhesion and abrasion are the most important parameters in braking of vehicles. Polymer composites undergo abrasive wear in most of the situations like earth moving equipments, pipelines, rock drilling and ore crushers etc.

Abrasive wear can be defined as wear in which hard asperities on one body, moving across a softer body under some load, penetrate and remove material from the softer body, leaving a groove. Abrasive wear can occur in two different forms: two-body and three-body

abrasion. Two-body abrasive wear is caused by hard protuberances or embedded hard particles forced against and moving along solid surfaces. The basic phenomenon in three-body abrasion is surface wear caused by loose abrasive particle which can freely move (roll or slide) between contact surfaces. These abrasive particles spend 90% of time by rolling and about only 10% of the time by positioning themselves between the solid surfaces. Hence the wear rate in the three-body abrasion is lower than that of the two-body abrasion. At the friction interface, the abrasive particles in the brake lining work` either in two-body abrasion mode or three-body abrasion mode and often changes from two-body mode to three-body mode or vice versa during the abrasion.

In current years, a lot of research has been committed to study the advantages of thermoset matrix in composite applications. Yousif et al. studied the three-body abrasive wear behaviour of chopped strand mat glass fibers reinforced polyester (CGRP) composite in different fiber orientation and summarised that CGRP exhibited better wear resistance in parallel orientation. Fillers and fiber reinforcements play an important role in determining the abrasive wear the polymer matrix composites. Suresha et al. studied the three-body abrasive wear of silicon carbide (SiC) filled in glass fabric reinforced epoxy (G-E) composites SiC decreased the specific wear rate of G-E composite. Suresha et al. and Ravikumar et al. studied the three-body abrasive wear of graphite/SiC filled in glass fabric reinforced epoxy composites and concluded that the graphite filler increased the specific wear rate and SiC decreased the specific wear rate of glass-epoxy composite. In another work by Suresha et al. reported that SiC when filled with glass fiber, reduces the wear volume and wear rate of vinyl ester significantly. Patnaik et al. investigated three-body abrasive wear of particulate filled glass-epoxy (G-E) composites and revealed that wear was more sensitive to variation in abrading distance. Suresha et al. studied the mechanical and three-body abrasive wear behaviour of vinyl ester composites reinforced with two and three dimensional E-glass woven fabric and concluded that under different abrading distances and loads, wear volume loss found to increase and that of specific wear rate decrease. Effect of silica sand and quartz abrasives on three-body abrasive wear of PA66/PP composite was carried out by Ravi Kumar et al. and observed high material removal rate with quartz abrasive than that of silica sand.

Polymer based composites are very attractive for pumps and agricultural equipments. By being lower in weight than steel parts that are traditionally used in these applications, polymer based composites hold the promise of reducing the weight and thus reducing the total cost. One possible way to widen the scope and usage of composite brake pad materials is to switch over from two-phase composite to multi-phase composite i.e., introduction of ceramic and lubricating fillers into the polymeric system having short fibers. This would enable the user to have minimum wear rate. However, the use of these functional fillers in actual service requires a careful cataloguing of the processing conditions employed and the attendant structure that follows. An approach of this kind would enable a correlation between structures and wear behaviour to emerge. Keeping this aspect in mind, it was decided to study the three-body abrasive wear behaviour of composite brake pad under different tribological parameters, such as applied load and abrading distance.

## Experimental Procedure

### *Materials and Method*

TABLE 1 MAJOR COMPOSITION OF COMPOSITE BRAKE PAD MATERIAL.

| S.No | Composition | % of composition |
|---|---|---|
| | **Binders** | |
| 1 | Phenol Formaldehyde powder | 29.04 |
| 2 | Cashew Nut Shell Liquid | 10.23 |
| 3 | Linseed oil | 0.65 |
| 4 | Hexamine | 0.27 |
| 5 | Carbon powder | 0.27 |
| | **Reinforcement** | |
| 6 | Fibre glass chopped strand | 0.27 |
| | **Fillers** | |
| 7 | Ferrosilicon | 15.07 |
| 8 | Antimony | 10.23 |
| 9 | Fire clay | 10.23 |
| 10 | Cashew friction dust | 8.93 |
| 11 | Rubber powder | 6.46 |
| 12 | Molykote powder | 2.69 |
| 13 | Graphite powder | 1.61 |
| 14 | Plaster of paris | 1.35 |
| 15 | Copper powder | 1.08 |
| 16 | Silicon carbide | 1.08 |
| 17 | Incense powder | 0.54 |
| | **Total** | **100** |

The required raw materials are listed in Table 1 for composite brake pad fabrication and were procured from two main suppliers: Mysore Pure Chemicals and Maxin Enterprises, Mysore, India. The fabrication of

composite containing nine major ingredients are listed in Table 1 and manufactured by hot compression moulding technique. The process of manufacturing a composite brake pad consists of series of operations including mixing, hydraulic pressing, cooling, post curing and finishing (Fig. 1). The ingredients

We blended for 20 min in a mixture until homogeneity was obtained. The mould and the die were initially preheated up to 80 $^0$C and cleaned by a thin layer of soap water (which acts as a barrier between the composite and the mould cavity). Then the mould cavity is filled with composite mixture, after filling back plate was put on mould and that was coated with adhesive to secure bonding between the friction composite and the plate. Then the perform pressure was varied from 5-10 tons for 5 s. The assembly was then subjected to hot pressing at a pressure of 40 ton, following the curing cycle as shown in Fig. 2. After curing, the composite brake pad was removed from the mould and again post-cured at 120 $^0$C for 60 min, 150 $^0$C for 60 min, and 170 $^0$C for 120 min. The process would be completed by cleaning and removing all the resinous layers and were coloured and coded. Abrasion test samples in accordance with ASTM G65-04 (2010) _ having size 75 mm x 25 mm x 6 mm were prepared from composite brake pad using abrasive cut-off machine.

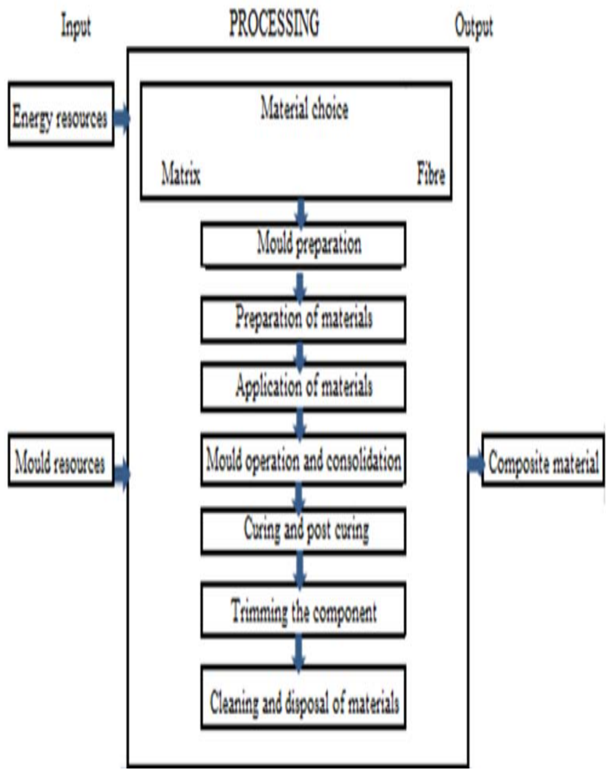



FIG.1 MANUFACTURING PROCESS OF COMPOSITE BRAKE PAD

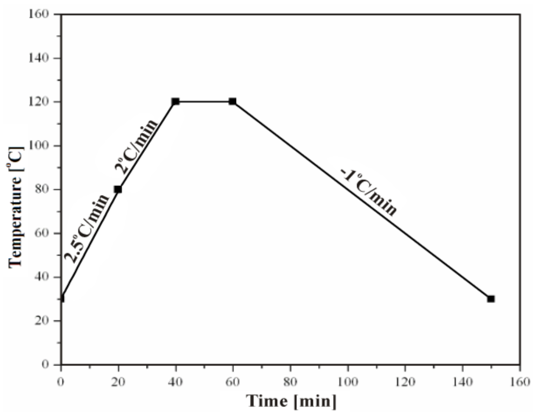



FIG.2 CURING CYCLE OF COMPOSITE BRAKE PAD

### *Density and Hardness*

Density of the composite brake pad was determined using a high precision (Mettler; Toledo) weighing balance by using the Archimede's principle. Hardness was measured on Rockwell hardness tester using L scale (Model: ZHR) of ASTM C748-98 (2010) standard. A test specimen size 50.8 mm x 50.8 mm x 6.35 mm is used to measure the hardness of composite brake pad. The test specimen is placed upon the machine and dial may be showing any reading. Preliminary minor load is applied (100 N) by turned the hand wheel, thereby raising the test specimen up against the ball indenter till the needle of the small dial is zero. Then the major load (500 N) is applied by pressing the crank of the machine and the time is given as 15 seconds, so as to make the load reach specimen completely. When the penetration is completed, the crank is turned in the reverse direction thereby withdrawing the major load but leaving the minor load applied. Then the hand wheel is rotated and the test specimen is lowered. At this stage, hardness of the test specimen can be directly read from dial scale.

### *Abrasive Wear Test*

The schematic representation of rubber wheel abrasion test set up is as shown in Fig. 3. In the present study, quartz sand (size of 200 - 250 μ) was used as abrasive. The abrasive particles of AFS 60 grade quartz sand were angular in shape with sharp edges.

The abrasive was fed at the contacting face between the rotating rubber wheel and the test sample. The tests were conducted at a rotational speed of 200 rpm. The feeding rate of abrasive was in the range of 255±5 g/min. The sample was cleaned with acetone in an ultrasonic cleaner and dried. Its initial weight was measured in a high precision digital balance (0.1 mg accuracy, Mettler; TOLEDO) before it was mounted in

the sample holder. The abrasives were introduced between the specimen and rotating rubber wheel which was composed of organic chlorobutyl material (hardness: Durometer A 58-62). The diameter of the rubber wheel used is 228 mm. The test specimen was pressed against the rotating wheel at a specified force by means of lever arm while a controlled flow of abrasives abrades the test surface. The rotation of the abrasive wheel was such that its contacting face moves in the direction of sand flow. The pivot axis of the lever arm lies within a plane, which is approximately tangent to the rubber wheel surface and normal to the horizontal diameter along which the load is applied. At the end of a set test duration, the specimen was removed, thoroughly cleaned and again weighed (final weight). The difference in the weight before and after abrasion was determined. At least three tests were performed and the average values obtained were used in the study. The experiments were carried out for loads of 20 and 60 N

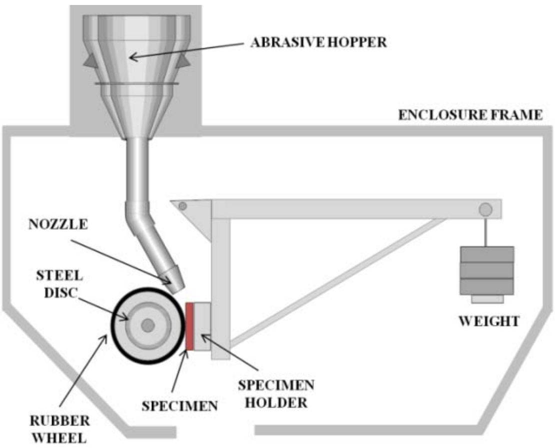



FIG.3 SCHEMATIC REPRESENTATION OF DRY SAND/ RUBBER WHEEL ABRASION TEST RIG

at a constant sliding velocity of 2.38 m/s. Further, the abrading distances were varied in steps of 500 m, from 500 to 3000 m. For the second longer duration test; say 1000 m distance, the abrasion tests were carried out on the very same wear track where the first (i.e. 500 m) shorter runs were involved. The wear was measured by the loss in weight, which was then converted into wear volume using the measured density data. The specific wear rate ($K_S$) was calculated from the following equation:

$$K_s = \frac{\Delta V}{L \times D} \quad m^3/\mathrm{Nm} \tag{1}$$

where $\Delta V$ is the volume loss, $L$ is the applied normal load and $D$ is the abrading distance.

Besides, the worn surfaces of the specimens were observed with a JEOL 840 Model scanning electron microscope (SEM). The samples were gold sputtered prior to use of SEM.

## Results and Discussion

### *Density and Hardness of Composite Brake Pad Material*

Table 2 shows the measured density and hardness of composite brake pad material. The hardness of composite brake pad material increases from 65 for the pure phenol formaldehyde to 85. The composite brake pad material is 1.3 times harder than pure phenol formaldehyde. The increase in hardness might be attributed to higher hardness of glass fiber and hard ceramic particles compared to phenol formaldehyde. Moreover, relatively uniform distribution of all phases within the matrix and decrease in interparticle distance within the matrix results in increase of resistance to indentation of phenol formaldehyde matrix. The measured density of the composite brake pad material is 1.56 g $cm^{-3}$. The increase in density of the composite is due inclusion of heavy densed materials into the phenol formaldehyde matrix.

TABLE 2 DENSITY AND HARDNESS OF THE COMPOSITE BRAKE PAD AND ITS COMPOSITION, QUARTZ ABRASIVE.

| S.No | Composition | Density (g/cm³) | Hardness |
|---|---|---|---|
| 1 | Phenol formaldehyde | 1.39 | 65(Rockwell-E) |
| 2 | Composite brake pad | 1.56 | 85 (Rockwell-L) |
| 3 | Quartz sand | 2.65 | 1160 (HV) |
| 4 | Silicon carbide | 3.21 | 2950 (HV) |

### *Abrasive Wear Volume*

Experimental results of abrasive wear tests revealed that the wear volume of composite brake pad was sensitive to variations of abrading distance and applied load as shown in Fig. 4. The wear volume loss of composite brake pad specimens as a function of abrading distance for the two different loads (20 and 60 N) and at a fixed rubber wheel speed of 200 rpm, exhibited low band width of wear volume loss at initial abrading distance which gradually increased with increasing abrading distance. It is also clear from the figure that the higher wear resistance is offered in lower load as compared to higher load. Suresha et al. investigated the three-body abrasive wear in epoxy composites reinforced with carbon and glass fibers and reported that increase in the abrading distance decreases the wear rate of glass-epoxy composite.

At lower abrading distance wear rate was high because, abrasive particles initially are in contact with low modulus matrix on the surface of the composite and at higher abrading distances lesser wear rate was observed due to resistance offered by glass fibers and SiC particles. Similar observations were made by Baswarajappa et al. in case G-E composite filled with SiC particles and reported that, as the abrading distance increases the hard SiC particulates resists the penetration of abrasive particles into the composite. As soon as the SiC particles are pulled due to continuous action, the matrix layer is removed resulting in the formation of the groove. Subsequently the glass fibers are subjected to action along with SiC particles, which provides additional abrasive wear resistance. Hence there was as an improved abrasive wear resistance of the SiC filled composite. But, in general, surface hardness is one of the most important factors that govern materials wear resistance and harder surface would have higher wear resistance.

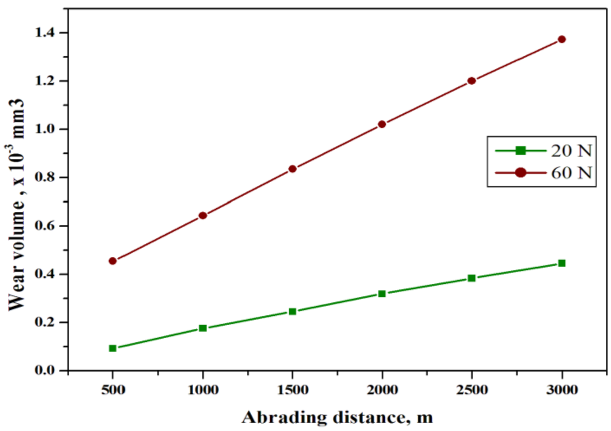



FIG.4 WEAR VOLUME OF BRAKE PAD AT 20 AND 60 N

To understand the synergistic effect revealed in Table 2, macro hardness of the specimens was measured. Along with glass fiber reinforcement and hard filler like silicon carbide, the multifunctional fillers like graphite, molykote, antimony and with some space fillers like ferrosilicon in binder are dispersed in a soft phase that is phenol formaldehyde matrix which increases hardness of composite and reduces wear rate. Suresha et al. studied the mechanical and three-body abrasive behavior of carbon-epoxy composite with and without graphite filler and concluded that the higher amount of graphite filler shows a least abrasion loss in the composite, and Harsha et al. investigated two-body and three-body abrasive wear of polyarlyetherketone (PAEK) composites and concluded that the graphite filler were detrimental to abrasive wear resistance compared to glass fiber reinforced PAEK composite.

Also, graphite along with molykote increased surface integrity, which prevents large scale fragmentation of phenol formaldehyde. Therefore, increased hardness on the surface results in increased wear resistance at lower load (20 N). However, at higher load (60 N) an upward positive gradient indicating greater wear volume loss at longer abrading distance was observed. This indicates that, as the applied load increases the wear volume loss was also increased and this is due to entrapment of the abrasive particles between the rubber wheel and the specimen, which induces high stress in the particles resulting in ploughing action on the specimen. Due to continuous removal of matrix materials on the surface of specimen, the grooves are formed and this groove further deepens as the load increases. After the removal of matrix layer, the micro cutting action is performed on the high modulus glass fiber. Chand et al. explained that abrasive wear increases with increase in applied load due to energy barrier at the junctional surface. In case of lower load, the energy produced by abrasive particles is not adequate to break the surface energy barrier and at higher load, particles gain energy from the high speed rubber wheel, split the barrier easily and strike the composite resulting in pit formation or plastic deformation of either matrix or fiber. In addition, the particles roll between the composite and rubber wheel causing plastic deformation of composite surface. Thus the higher wear volume loss is observed with increase in applied load.

In the case of higher load, the wear mechanism were micro-cutting marked as (marked as M), ploughing (marked as P) and fragmentation of wear debris in the matrix and excessive deterioration of fiber surface followed by tearing the fiber transversely (marked as T) as shown in Fig.7 (b), while in lower load, the wear mechanisms were micro-cutting in the resin matrix as shown in Fig.6 (a).The worn surfaces were examined using scanning electron microscopy (SEM) and SEM pictures give credence to the three-body abrasive wear behaviour by way of interpreting the results with the wear mechanism such as fiber fracture, matrix deformation, debonding of fiber with the matrix.

### *Specific Wear Rate*

Fig. 5 shows the specific wear rate ($K_s$) of composite brake pad samples as a function of abrading distance for the two loads to a fixed rubber wheel at a speed of 200 rpm. The specific wear rate of brake pad at 20 N load is in the range ($0.74 \times 10^{-11}$ - $0.93 \times 10^{-11}$) $m^3/N$ m and 60 N load lies in the range ($0.76 \times 10^{-11}$ -$1.52 \times 10^{-11}$)

$m^3/N$ m. In three-body abrasion, movement of abrasive particle which is rolling or sliding depends on particle morphology, size, applied normal load, surface hardness and hardness ratio of contacting surfaces. In such cases, the loading condition was maintained so that a fixed concave surface is generated irrespective of the micro constituent phases present on the composite sample surface. The required wear resistant material finding applications in above wear situations must possess high strength with adequate toughness and ductility. Such properties can be achieved through incorporation of hard dispersoid particles into a relatively soft matrix called phenol formaldehyde composites.

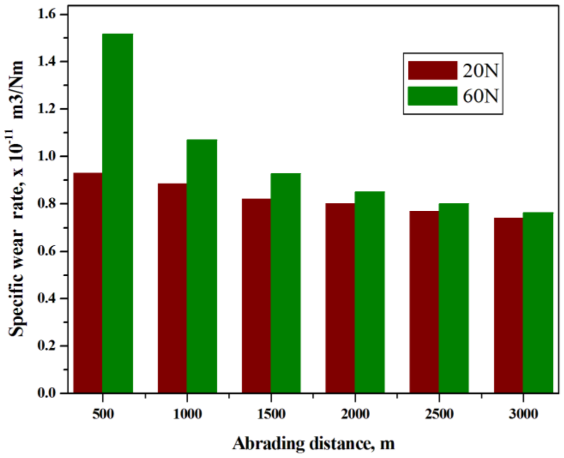



FIG.5 SPECIFIC WEAR RATE OF BRAKE PAD AT 20 AND 60 N

The phenol formaldehyde matrix possessing high strength/hardness improved the abrasive wear resistance by decreasing the depth of penetration by the quartz abrasives as well as offering a better support to the dispersoid phase. The reinforced (dispersoid) phase particles such as glass fibers SiC and ferrosilicon strengthens composite and molykote acts as lubricant which are effective barriers in preventing large scale fragmentation of phenol formaldehyde.

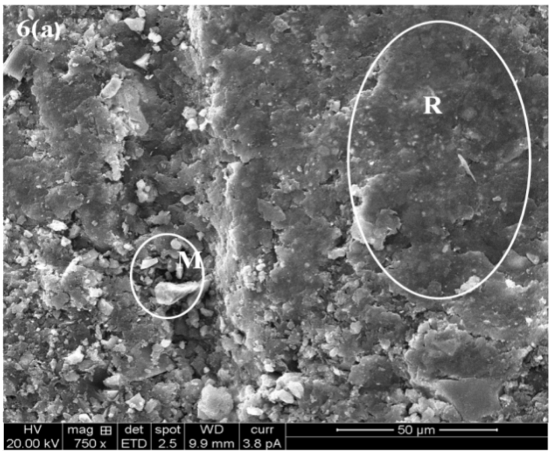
Thus the properties of matrix, dispersoid phase and dispersoid matrix interfacial bonding play a significant role in controlling the wear rate. When abrading distance is varied from 500-3000 m, the wear volume loss of composite increases however reverse trend is observed when plotted for specific wear rate. When abrading distance is increased, more number of glass fibers is exposed to abrasion process. The hardness of silicon carbide and glass fibers exhibit resistant to abrasion and in turn, quartz particle has to work more or high energy is required to bring about fiber breakage. As abrasion proceeds molykote particle which is self lubricant, is protruded out from sample surface which get smeared at the friction interface and produce lubrication and reduced the specific wear rate. Thus the rate at which material removed with respect to abrading distances decrease. Researchers indicate that particles of hardness extremes improve the wear resistance of polymer based composites. Hard ceramic particles (e.g. SiC, $Al_2O_3$, slicon dioxide and boron carbide) and soft lubricants (e.g. $MoS_2$ and graphite) have been used to increase the wear resistance of the epoxy matrix. Hard and soft fillers involve different mechanisms for increasing the wear resistance of a composite. Previous studies of composite wear concentrated on fiber reinfroced polymer based composite with hard and soft fillers. Suresha et al. investigated the three-body abrasive wear in epoxy composites reinforced with carbon and glass fibers and stated that the higher abrading distance/load the higher would be the wear volume; specific wear rate decreased with increasing abrading distance and increased with load. Moreover, linear wear hypothesis revealed close approximation of wear performance of friction material with prediction of pad life by Pavelescu et al. Thus, in this present work similar observation was found which agreed with the conclusions stated in the literature [17 and 18]. Increased $K_s$ of composite samples with increase in applied load could be attributed to increased contact pressure between the abrasive particles and the sample surface. This results in increased depth of penetration on the sample surface by the abrasive particles. This could be very well understood on the basis of observation of the greater tendency for the fracture and partial removal of the constituents shown in the SEM pictures (Figs. 6 and 7) and various features are discussed in the section scanning electron microscopy.

### *Morphology of Worn Surfaces*

To correlate the wear data better, SEM photomicrographs of abraded samples were taken at different loads and abrading distances to find out predominant wear mechanisms. The worn surface of brake pad under 20 N load at 500 m distance is shown in Fig. 6 (a). The composite surface exhibits resin rich (marked as R) surface layer with less voids and debris. The presence of resin layer improved the bonding and surface integrity with high fiber-matrix adhesion.

It is clear from Fig. 6 (b) that certain amount of voids (marked as V) are generated after abrasion process under 20 N load and 3000 m distance However voids are localised and minimal due to wear resistance offered by reinforced glass fiber and SiC. This allowed

less matrix phase wear out by lowering the fiber breakage. Hence the resultant worn surface is relatively smooth with less micro cracks and voids.



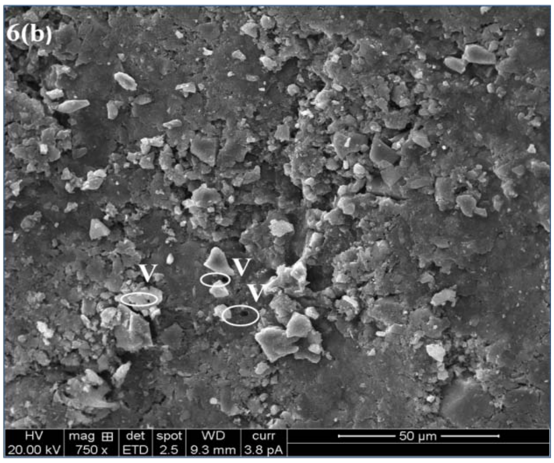




FIG.6 WORN SURFACE PHOTOGRAPHS OF COMPOSITE BRAKE PAD: (a) 500 m, 20 N and (b) 3000 m, 20 N

Fig. 7 (a) illustrates the worn surfaces of brake pad under 60 N load at abrading distance of 500 m. With subsequent application of load damage to reinforcement fibers and fillers is high resulting in fiber removal from the surface. Increase in contact temperature enables accelerated damage of matrix in interfacial region. Fiber debonding (marked as D), crack propagation (marked as C) and broken fibers (marked as B) are evident predominantly along the direction of flow of abrasives. As a result the surface is left out with imprints of separating fibers.

At higher abrading distance of 3000 m under 60 N load, deep furrows are exhibited on the surface which corresponds to abrading direction and shown in Fig. 7 (b). Micro-ploughing (marked as P) and transverse bending effect of sharp quartz abrasives cause fragmentation of fiber and made them to pullout from matrix lead to high matrix debris (marked as M) formation. This debris further decreases the wear resistance of composite through three-body abrasion

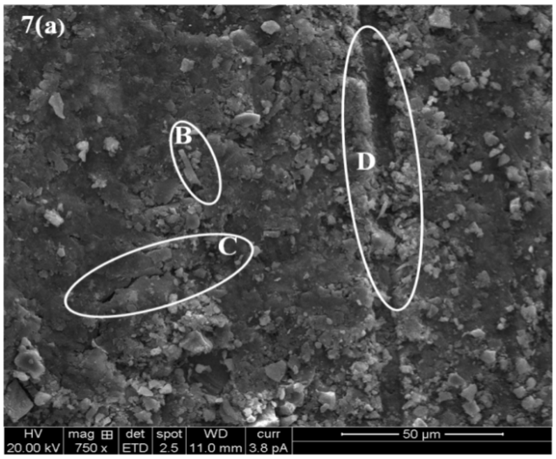




FIG.7 WORN SURFACE PHOTOGRAPHS OF COMPOSITE BRAKE PAD: (a) 500 m, 60 N and (b) 3000 m, 60 N

effect. Due to surface fatigue by repeated abrasion of quartz, transverse fibers are also damaged which produce voids in the matrix. Interfacial debonding caused poor adhesion between filler, fiber and phenol formaldehyde matrix resulted in accelerated breakage of matrix.

## Conclusions

From three-body abrasive wear studies of composite brake pad, the following conclusions can be drawn;

- The wear volume loss of composite brake pad increases with increasing abrading distance/ load.
- Specific wear rate increases with applied load and decreases with increasing abrading distance.
- Glass fibers and abrasive fillers were effective in reducing the specific wear rate of phenol formaldehyde. It is reasonable to deduce that binders, abrasives would increase the adhesion of glass fibers, SiC and phenol formaldehyde matrix.

- Brake pad exhibited low band width of wear volume loss at initial abrading distance which gradually increased with increasing abrading distance. Applied load is sufficient to induce stress at contact area within experimental conditions.
- The reinforced (dispersoid) phase particles such as glass fibers, SiC strengthens composite and molykote acts as lubricant which are effective barriers in preventing large scale fragmentation of phenol formaldehyde.
- SEM studies of worn surface indicates the presence of resin layer which improved the bonding and surface integrity with high fiber-matrix adhesion at 20 N load.
- When the load is increased from 20 to 60 N microcracks are formed followed by fragmentation of the constituents in composite brake pad.
- Ploughing, cracking wear mechanism and accelerated breakage of fibers in composite are evident under high load.

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